Treemap Visualization for Space Situational Awareness

John D. Ianni
Air Force Research Laboratory, Wright-Patterson AFB, OH

Zac Gorrell
Valepro, LLC, Colorado Springs, CO

ABSTRACT

Making sense of massive data sets is a problem for many military domains including space. With unwieldy "big data" sets used for space situational awareness (SSA), important trends and outliers may not be easy to spot – especially not at-a-glance. One method being explored to visualize SSA data sets is called treemapping. Treemaps fill screen space with nested rectangles (tiles) of various sizes and colors to represent multiple dimensions of hierarchical data sets. By mapping these dimensions effectively with a tiling algorithm that maintains an appropriate aspect ratio, patterns can emerge that often would have gone unnoticed. The ability to interactively perform range filtering (in our case with sliders) and object drill-downs (hyperlinking the tiles) make this technology powerful for in-depth analyses in addition to at-a-glance awareness. For one SSA analysis, the tiles could represent satellites that are grouped by country, sized by apogee, and colored/shaded by the launch date. Filter sliders could allow apogee range or launch dates to be narrowed for better resolution of a smaller data set. The application of this technology for the Joint Space Operations Center (JSpOC) Mission System (JMS) is being explored on a DARPA Small Business Innovative Research (SBIR) effort as a plug-in to the existing User-Defined Operational Picture (UDOP). In addition, visualization of DARPA OrbitOutlook small telescope data will be demonstrated. This research will investigate what SSA analyses are best served by treemaps, the best tiling algorithms for these problems, and how the treemaps should be integrated into the existing JMS UDOP workflow. Finally, we introduce a variation of treemaps that help leaders allocate their time to tasks based on importance and urgency.

1. TREEMAP VISUALIZATION CONCEPT

Treemapping is a visualization technique for large data sets that fill screen space with rectangles (tiles) of varying sizes and colors [9][2][11]. Size and color is mapped to parameters of the data in logical ways to allow an analyst to identify trends and outliers. Typically tiles are arranged into groups to create a more logical organization. For example, a presidential election treemap can display every county in the United States grouped by state (Fig. 1). The counties in this example are either blue for democratic leaning or red for republican leaning. Color shade reflects how much the county leaned toward the political party with darker shades indicating a strong leaning. Size indicates the population of the county. The group's (i.e., state's) title bar color reflects the overall leaning of the entire state.

Many treemap implementations provide a way to filter data for more focused analyses. For example, an analyst looking at Fig. 1 may want to see how well their candidate is performing in large counties or just see the states where the race is within the margin of error. In addition to filtering, the user is often able to map different parameters to rectangle size or color. For example, they may want to compare age groups instead of counties.

If there is supporting data, the user can click on any tile to drill down for detailed information. This can be virtually any display like a table with textual metadata, a hyperlink to a web page, or another treemap. Animation can be used to "explode" the tile to enhance the hierarchical awareness as a user moves up and down the tree [6].
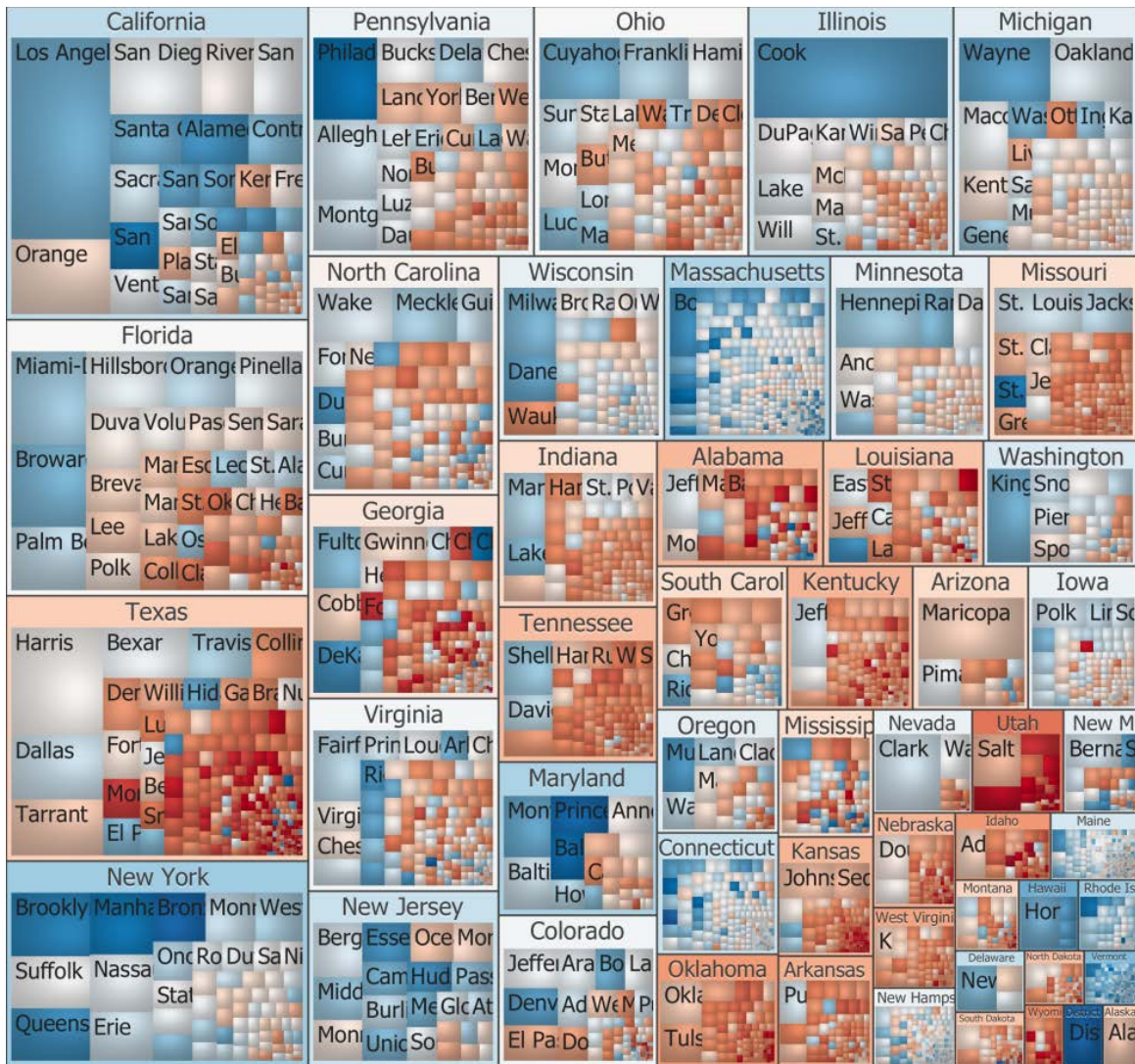
Fig. 1: Presidential Election Treemap [7]

Some wonder why not use a geographic map of the United States instead of a treemap to display election trends. Certainly there is a place for geospatial visualizations but, in this case, population is more central to the analysis than geolocation or area. Actually what matters the most in U.S. presidential elections are the number of delegates which is correlated to population. Alaska is almost 430 times the geographic size of Rhode Island yet, due to the population differences, Alaska has three delegates compared to Rhode Island's four. So an alternative treemap to Fig. 1 could be to have tiles represent delegates. Since all delegate votes are equal, the tiles would be the same size but the number of tiles in each state would range from 3 to 55.

2. TREEMAPS FOR SPACE OPERATIONS

Although geospatial and temporal understanding is important for higher-level awareness in space operations, we have observed that analysts often work more with the numerically-oriented data for mission critical tasks [1]. Certainly the spatial considerations are important, but alone do not provide the quantifiable evidence that is often needed to take action such as maneuvering a satellite. Therefore treemapping seems to be a powerful option.

Originally this research aimed to improve SSA for multinational teams in the Combined Space Operational Center (CSpOC). Treemaps were believed to be a useful method to convey information that was independent of language, culture or nationality. Although this continues to be a consideration for this research, we felt that it was important to first mature this technology for the users in the United States. Thus we were able to demonstrate many types of analyses on data collected from space-track.org [10]. The following are some examples of treemaps developed in the early research phase.

2.1. **Collision Avoidance**

Fig. 2 below illustrates a Collision Avoidance scenario depicting approximately 4,000 orbiting objects grouped by the object's country, sized by the object's apogee, and colored by the possibility of containing a potential conjunction. The possibility of a conjunction is indicated by a red color while those objects not meeting the conjunction criteria are indicated by a green color. Any object that has a potential conjunction within 5 km of another resident space object (RSO) within a defined 72 hour period of time is colored red in this scenario. To achieve the actual source of this knowledge, we have several services running in the background on the application/database server including a propagator which determines if/when a given object will collide (or intersect with) another object, estimates the time of that conjunction, and determines the closeness and delta velocity of the objects involved in the conjunction. The results of the propagator are then programmatically inserted into the database where they then become available to the user's views. We have developed the propagator algorithms and the database tables that store the propagator's output, and relationships with other tables that maintain information about the referenced objects.
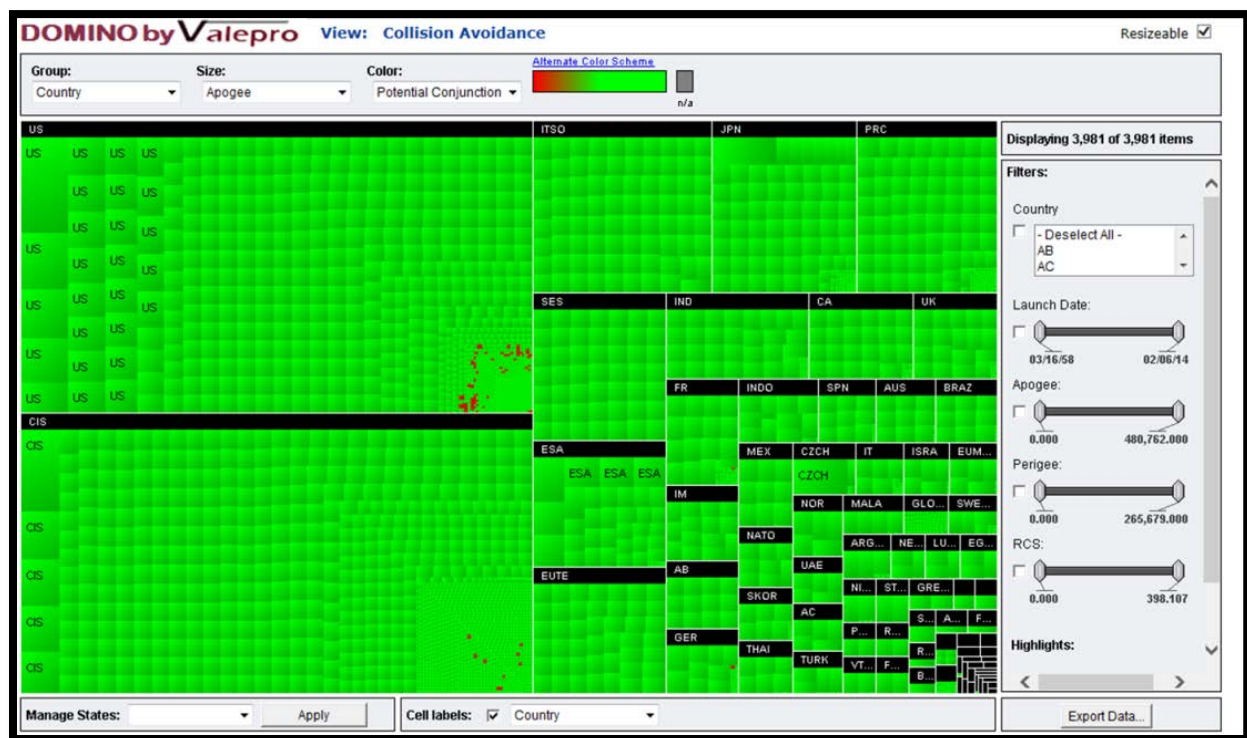

Fig. 2: Collision Avoidance Scenario – Top-Level Treemap

After seeing the first view of the Collision Avoidance scenario dominated by green cells, let's zoom into the U.S. to get a better view of some of the red cells of interest. If we click our mouse on the black U.S. text, we'll get the option shown in Fig. 3 below to "Zoom In".
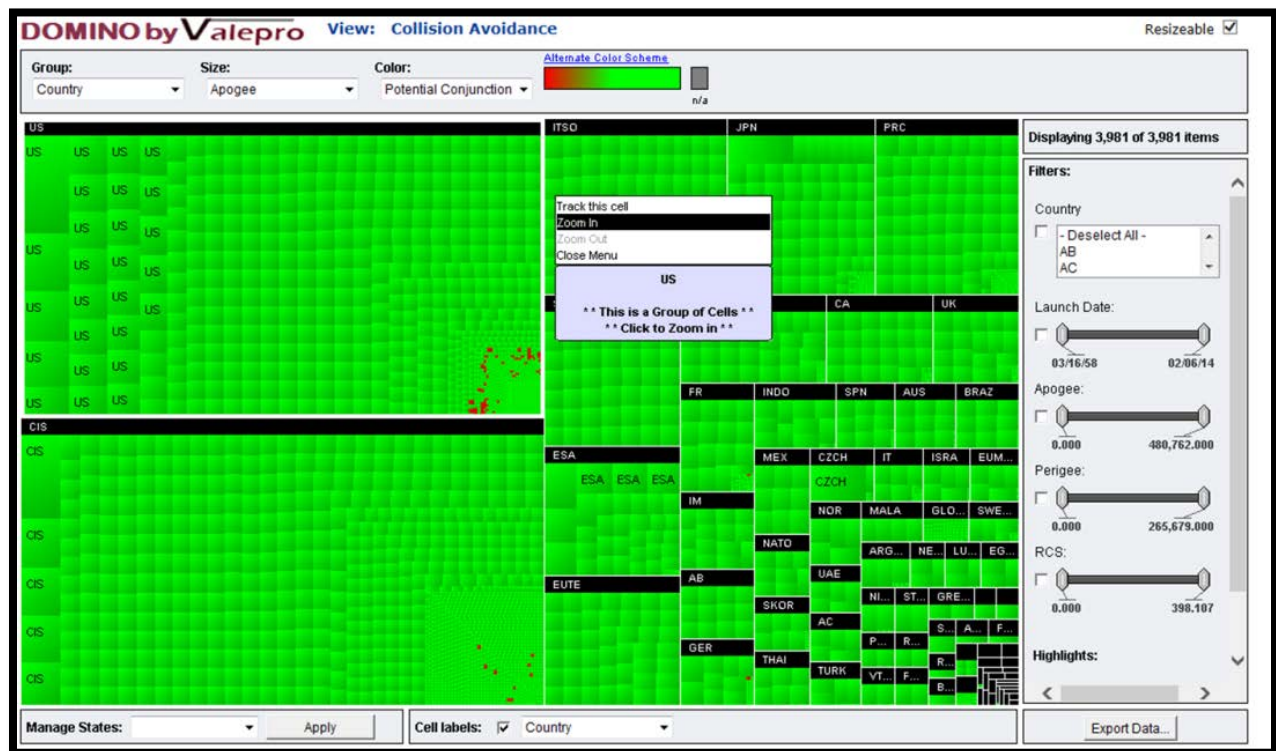

Fig. 3: Collision Avoidance Scenario - Zooming In on the U.S.

Now that we're zoomed into U.S. only results, if we right click on a red cell of interest, the content of the cell that we clicked on will be overlaid on the display as shown in Fig. 4. The overlay gives detailed information about the orbiting object that the cell represents. We also notice that we have the opportunity to obtain even more information about the conjunction by clicking on "Conjunction Detail" for the satellite that is selected.
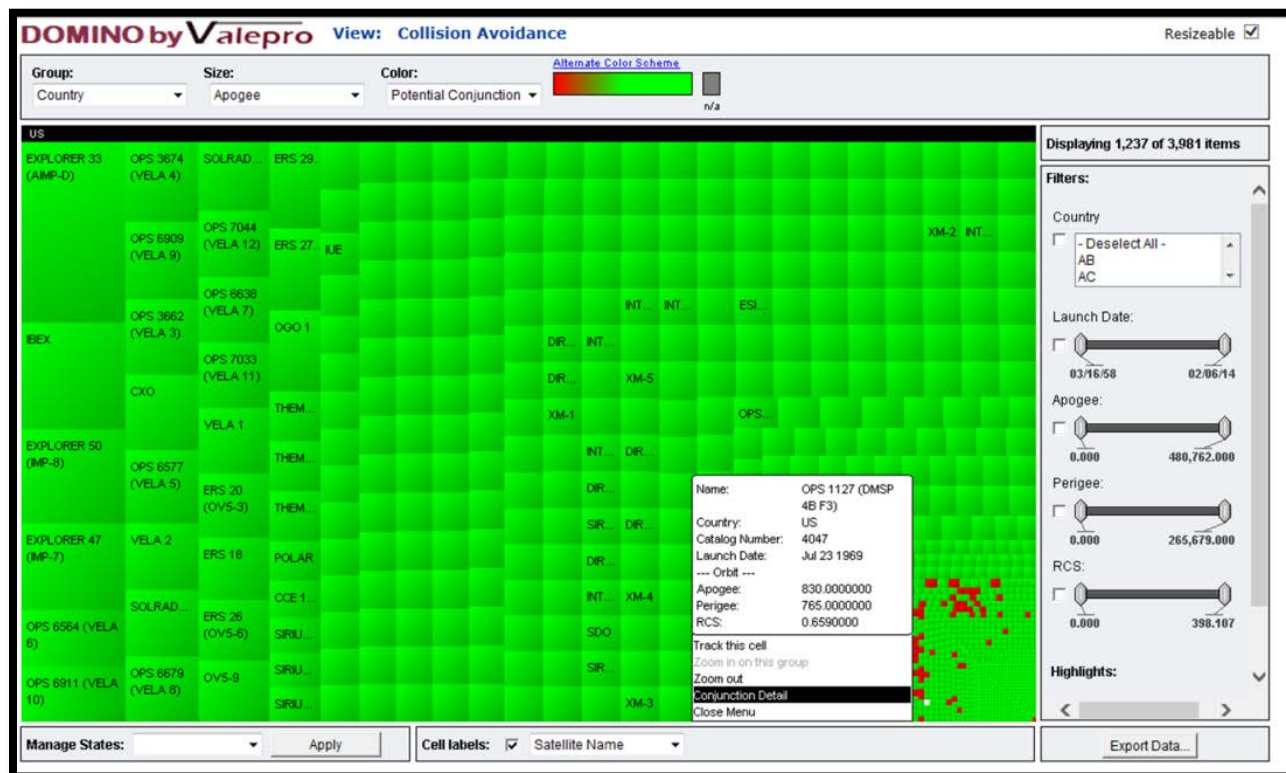

Fig. 4: Collision Avoidance Scenario - Treemap Showing U.S. Only

After clicking on "Conjunction Detail", we now get a lower-level view of the supporting treemap structure. Each of the ten rectangles contained in Fig. 5 below represent a potential conjunction within 5 km of the OPS 1127 satellite over a 72 hour time period.

In this view, we've chosen to Group by "Conjunction Date and Time", Size by "Delta Velocity", and Color by "Closest Approach". Therefore, rectangular cells that are large contain high values for delta velocity while those that are small contain lower values for delta velocity. Similarly, cells that are bright red contain potential conjunctions within a relatively short distance, while those that are colored yellow contain potential conjunctions closer to 5 km at the point of closest approach.

In this example, one can see that when we hover over the red rectangular cell in the lower left, the OPS 1127 satellite was predicted to come within 2.64 km of a piece of Iridium 33 debris at a closing velocity of 14.3 km/sec back on February 11th, 2014.

From this example, one can see how the interactive nature of this treemapping product can be very useful to operators in quickly investigating satellite anomalies and events of interest.
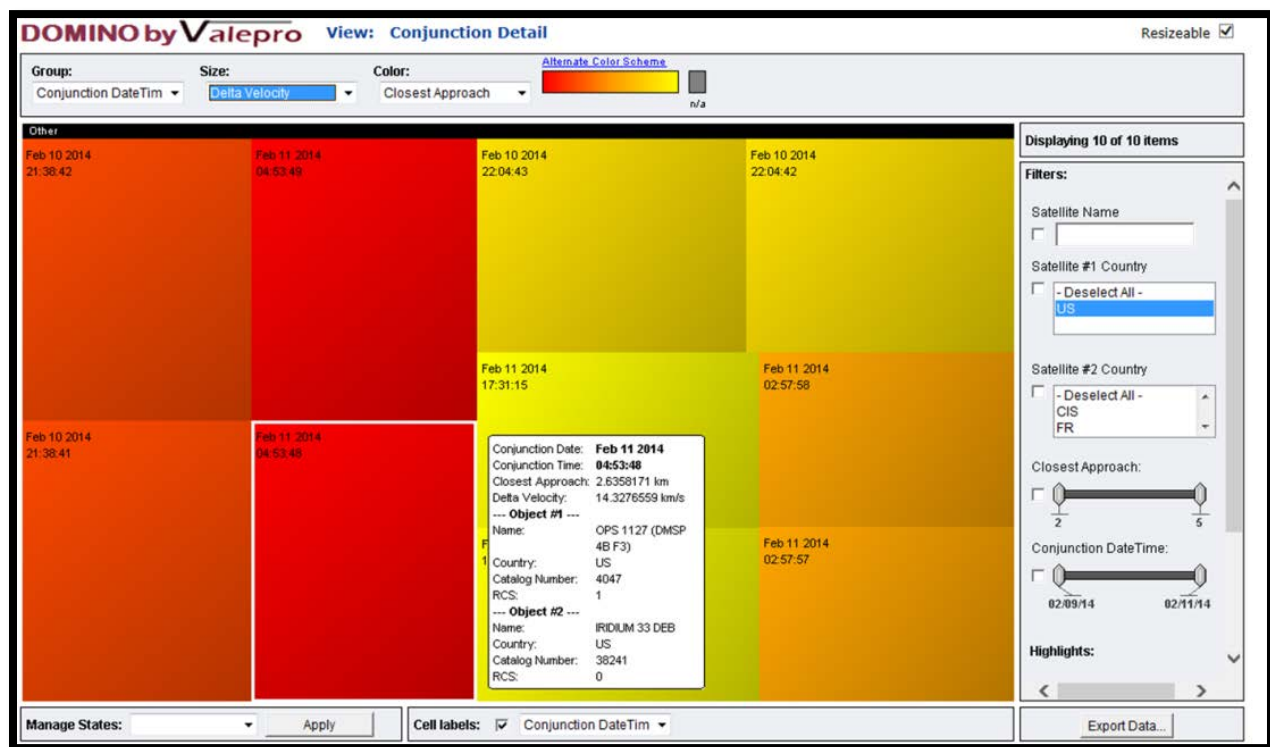

Fig. 5: Collision Avoidance Scenario - Conjunction Details for U.S. OPS 1127 Satellite on Feb 11th, 2014

2.2.   Space Catalog

The next scenario we will discuss is the Unclassified Space Catalog Overview (USCO). Fig. 6 shows over 17,000 cells that represent orbiting objects that we have obtained from our https://www.space-track.org account. In this initial view, RSOs are grouped by Country, the size of the cells is based on apogee of the RSOs, and the cells are colored by Launch Date with white cells indicating objects that have been launched a number of years in the past (dating back to 1958), and dark blue cells indicating objects that have been launched recently (within the last few years). From this initial view, one can see that the country accounting for the majority of RSOs in the Unclass Space Catalog according to Space-Track.org is the Commonwealth of Independent States (CIS), followed by the United States (US), and then France (FR) and the People's Republic of China (PRC).

It's important to note in this initial view that the Group by, Size by, and Color by user controls are all located along the top of the treemapping product, various filters and slider bars are located along the right hand side, and cell labeling capabilities are located on the bottom.
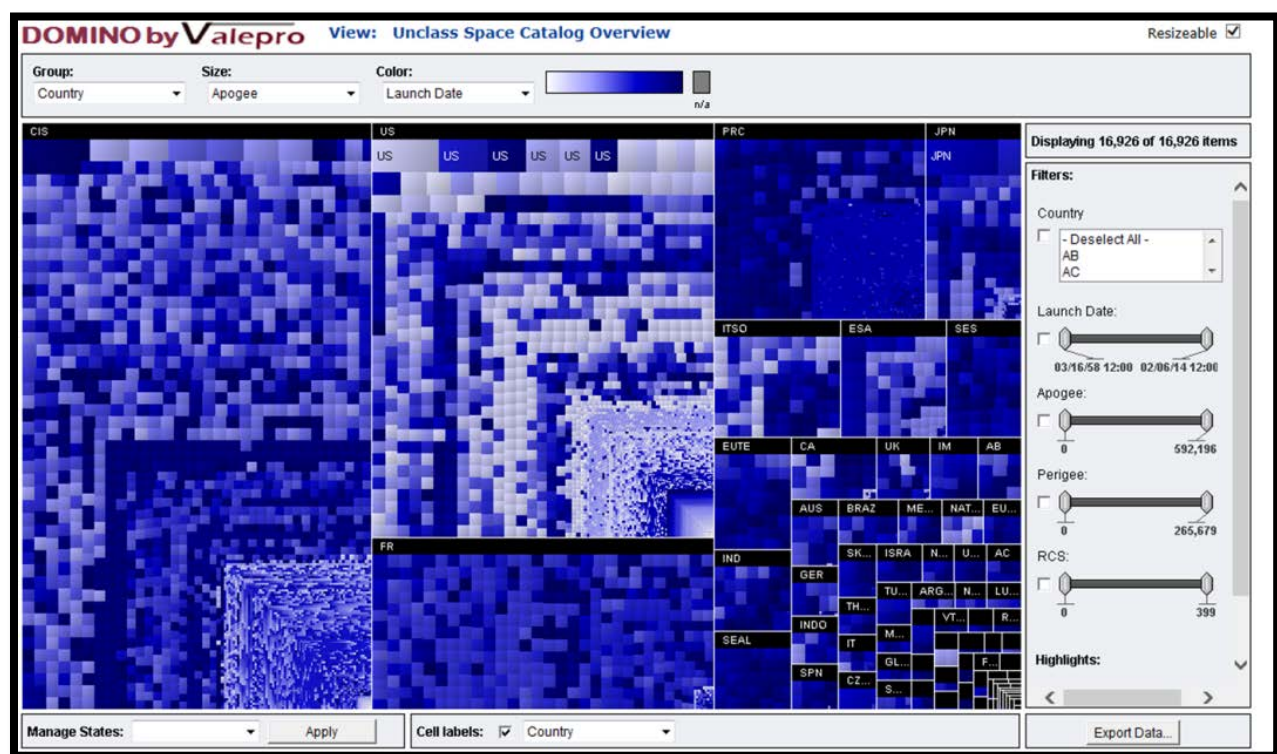

Fig. 6: Unclassified Space Catalog Overview Scenario - Top-Level Treemap

In Fig. 7 shown below, we have chosen to select "Size By Radar Cross Section (RCS)". We're still looking at the same Unclassified Space Catalog scenario, but we've simply chosen a different "Size by" option, and the view has updated accordingly. As you might expect, you can now see the largest cell in the treemap is the International Space Station (ISS) cell located in the bottom center of the screen. By hovering the mouse over the International Space Station in this example, a pop-up window comes up displaying information about that particular asset.
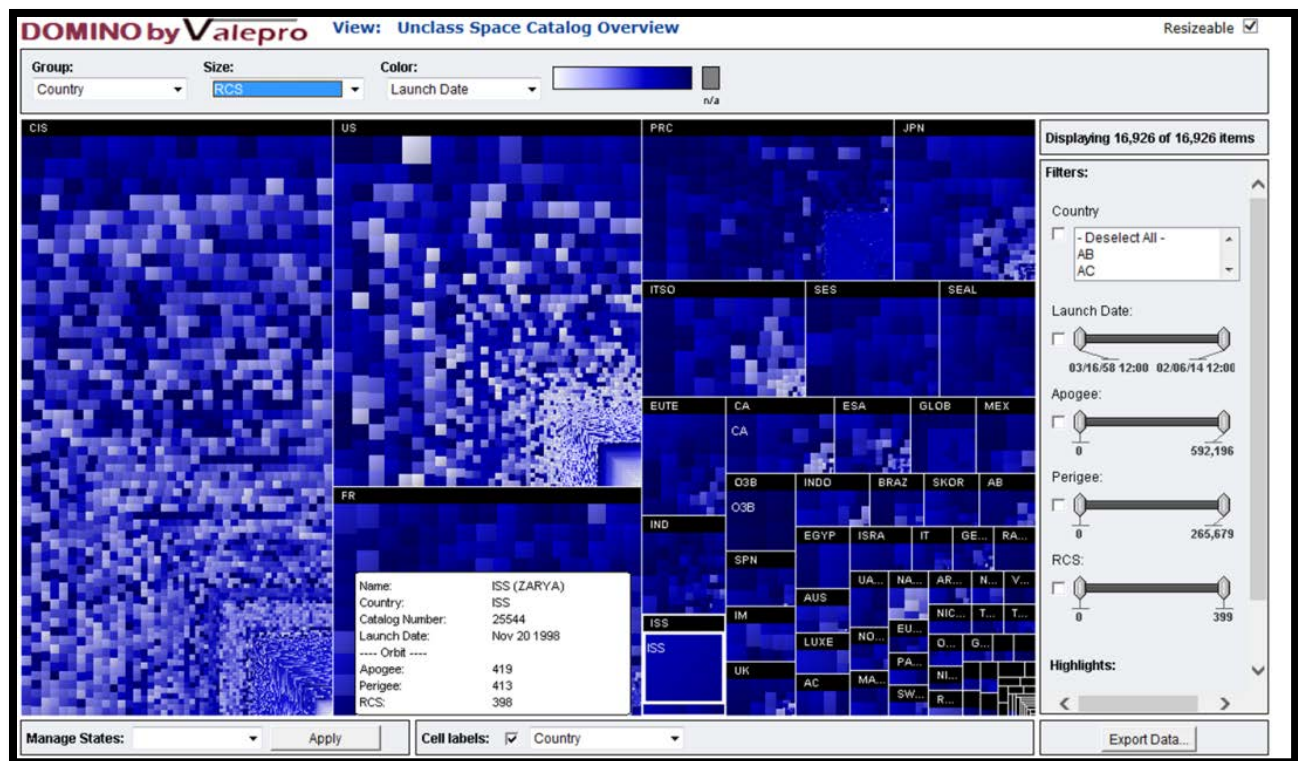
Fig. 7: Unclassified Space Catalog Overview Scenario - Treemap Sized By RCS

In Fig. 8 below, we have chosen to filter the results of the scenario to display only RSOs originating from the United States. We accomplished this by using the "Country" filter located on the right hand side of this view. As one can see, we are now displaying 5,053 objects out of the nearly 17,000 objects contained in this scenario (see upper right hand corner of the product display where is says, "Displaying X out of Y items"). In this view, we have also chosen to turn on "Cell labels", and we've selected "Name" as the field that we want to label each cell with.
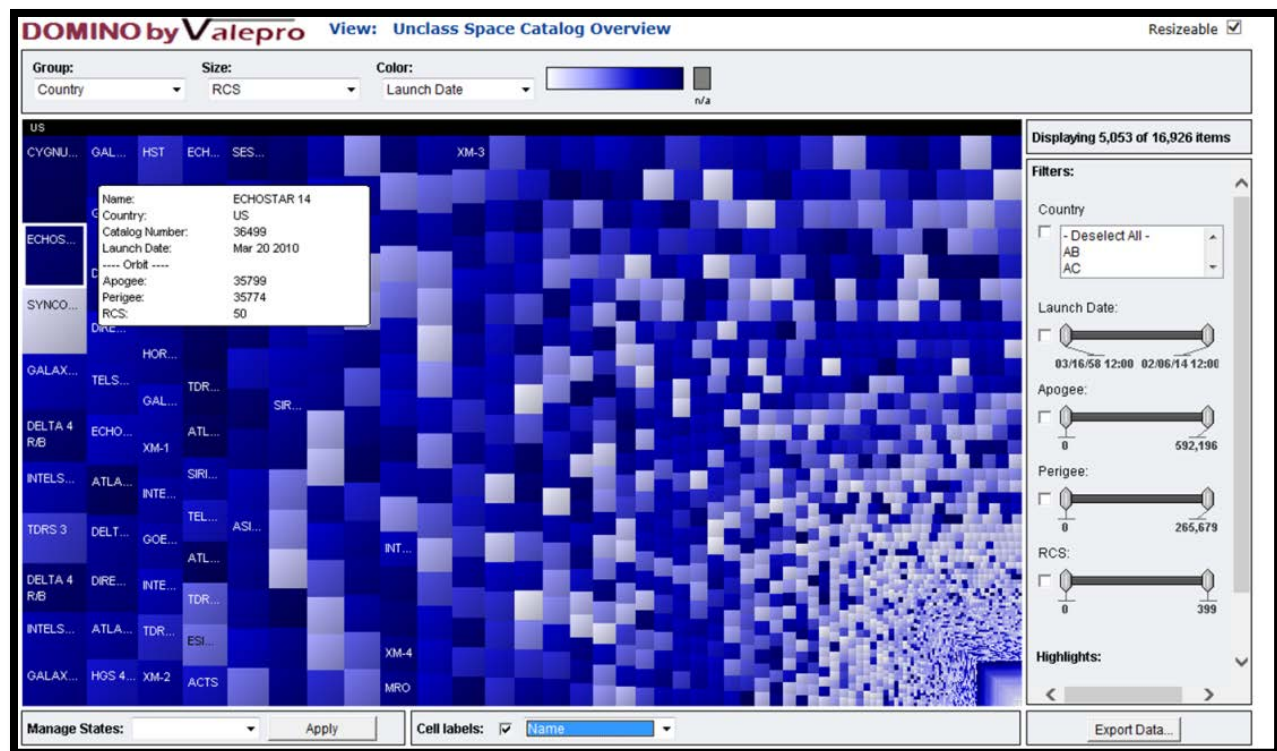
Fig. 8: Unclassified Space Catalog Overview Scenario - Results Filtered to U.S. Only and Cell Labels Added

Now that we have refined our results by applying the "U.S. Only" filter, let's further refine our results by using the "Launch Date" and "RCS" slider bars to investigate only U.S. satellites launched in the last 20 years with an RCS value greater than 24. We can see from Fig. 9 below that the number of results in this treemap view reduces down to only 29 total objects.

Through this quick example, one can see how a user can easily navigate around the treemap using a combination of Group by, Size by, and Color by options, coupled with filters and slider bars to very quickly hone in on the data of interest.
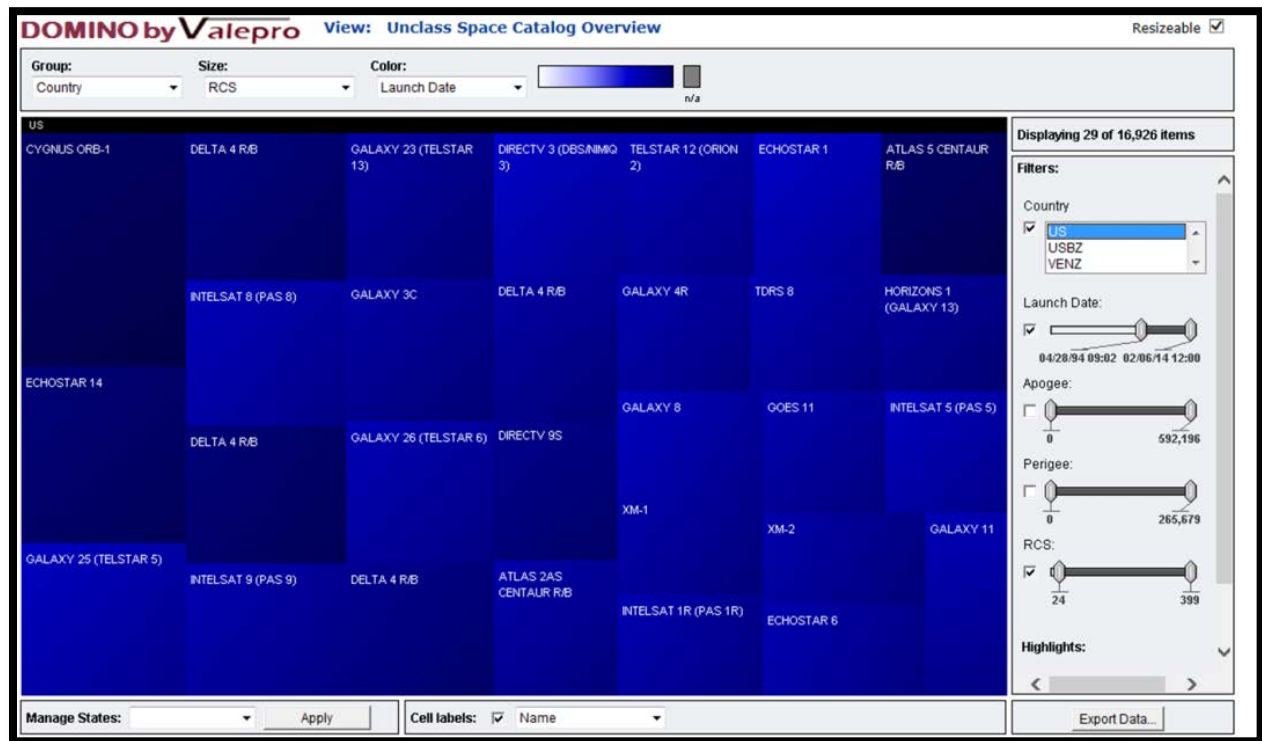
**Fig. 9: Unclassified Space Catalog Overview Scenario -
U.S. Satellites Launched in the Last 20 Years with RCS Values Greater Than 24**

3. ORBITOUTLOOK TREEMAPS

OrbitOutlook (O2) is a Defense Advanced Research Projects Agency (DARPA) program that aims to determine when satellites are at risk by leveraging more diverse sources of SSA and employing tools to better exploit this data [4]. O2 aims to supplement the data provided by the current 29 space surveillance sensors that make up the U.S. Space Surveillance Network (SSN) by leveraging new radar and optical telescope sensors in distributed locations – such as observations from amateur astronomers and the academic community. The data from these sensors will be stored in a centralized database then analyzed using validation algorithms that determine confidence metrics and quantify the bias and measurement errors present in each observation.

Currently, there is no centralized service to visualize the SSA data being collected by these additional sensors or ways to integrate and highlight the effectiveness of these new validation algorithms. Treemapping technology will be used to provide a "big data" visualization service for O2 that allows the additional observations to be viewed in a single display to decrease the time required to determine when satellites are at risk from orbiting space debris or intentional acts.

Fig. 10 provides a high-level Operational View 1 (OV-1) conveying how treemapping technology will be used to support O2. The sensor icons on the globe represent small telescopes and non-traditional sensors used to collect SSA observations. These observations are then stored in the form of astrometric and radiometric data in a database called the OrbitOutlook Data Archive (OODA). Validation algorithms are run on the data to assess confidence metrics, and bias and measurement errors associated with the observations. This post-processed data is then viewed using treemapping technology to allow an observer to quickly identify trends in the data, spot outliers, and detect the confidence that can be attributed to the additional observations from non-traditional SSA sensors. The goal is that through the use of treemapping technology to visualize the data in the OODA, operators and decision makers can increase their confidence and reduce the amount of time that it takes to determine when satellites are at risk.
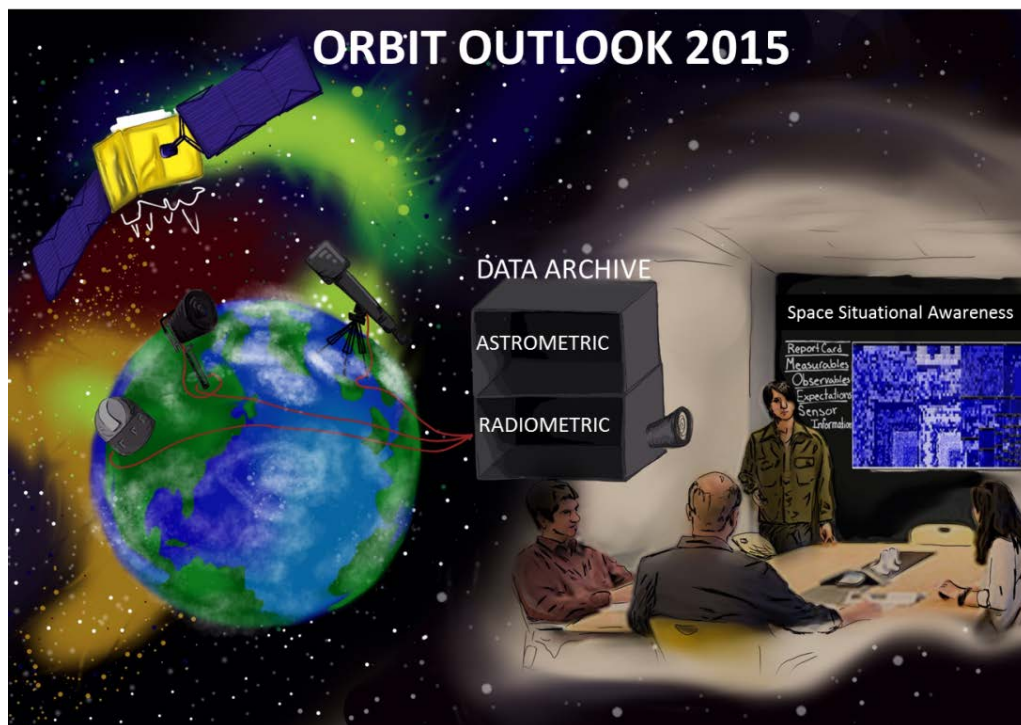

Fig. 10: High-Level OV-1 - Treemapping Applied to DARPA O2 Program

4.   COMMANDER'S TREEMAP

Although treemapping can be an effective tool for analysts, the visualizations may be too detailed for leaders, like military commanders or CEOs, who mostly need the big picture. In particular leaders need to assess what areas of interest most require their attention at a given time. This prioritization can be assessed as a function of importance and urgency as noted by former U.S. President Dwight D. Eisenhower [5][8] and Covey, et al [3]. Eisenhower's Urgent/Important Principle assesses what is important and what is urgent to allow leaders better allocate their time to the most pressing issues. Situations with high importance and high urgency trump less important or urgent situations. The dilemma comes when you have multiple situations that are both important and urgent. To address this high-stress situation, we felt that treemaps could provide a way to visualize priorities by assigning or calculating values for importance and urgency.

The concept uses treemap groups to represent the areas of interest with graphical icons and textual names used to quickly recognize the group's theme. The details of the group are summed up into a single alert state – say green-yellow-red – rather than showing the detailed treemap of that group. The alert colors are user selectable but our examples typically use green to convey the normal state, yellow to indicate caution state, red to indicate critical state and blinking red to indicate a highly critical state. In addition, blue can be used to indicate positive opportunities. Of course, shading can be substituted for color for those who are color blind but we believe it is important for this concept to have a limited number (say 3-5) of discrete colors rather than a continuum.

The size of the rectangle is a factor of importance multiplied by urgency. Often the importance will be a fixed number that conveys the relative importance of that topic to the commander. This will define the size of the group compared to other groups in normal operations. We believe the urgency factor, however, may either be fixed number or an algorithm based on the state of affairs. For example, the urgency factor may grow based on the number of satellite outages.

If the importance and urgency factors are optimally chosen, the treemap in theory will convey what areas require attention first.   In the example provided in Fig. 11 and Fig. 12, fixed urgency factors are pre-selected based on discrete states. A "yellow" alert state may result in a doubling in size whereas a more significant "red" state may cause the rectangle to grow much more significantly. Accordingly, the group's rectangle would move toward the upper left of the treemap according to the tiling algorithm we use.

Fig. 11 provides a notional example of how the Commander's Treemap concept would convey a major space weather event. In routine operations, this commander has determined that threats (i.e., intentional acts of aggression) are the most important area to monitor whereas space weather is down on his list of concerns. Thus the Threat Group is the largest rectangle (upper left treemap in Fig. 11) and the Space Weather Group is the smallest. But a major solar event which seriously threatens all space assets causes the Space Weather Group to grow significantly. Note that the rectangle not only grew and became red, but it also automatically repositioned to the upper left. [This repositioning of largest rectangles to the upper left is a typical behavior of treemaps.] In addition to color, blinking can be used to convey highly urgent events but should be used sparingly and temporarily to avoid distraction and desensitization.
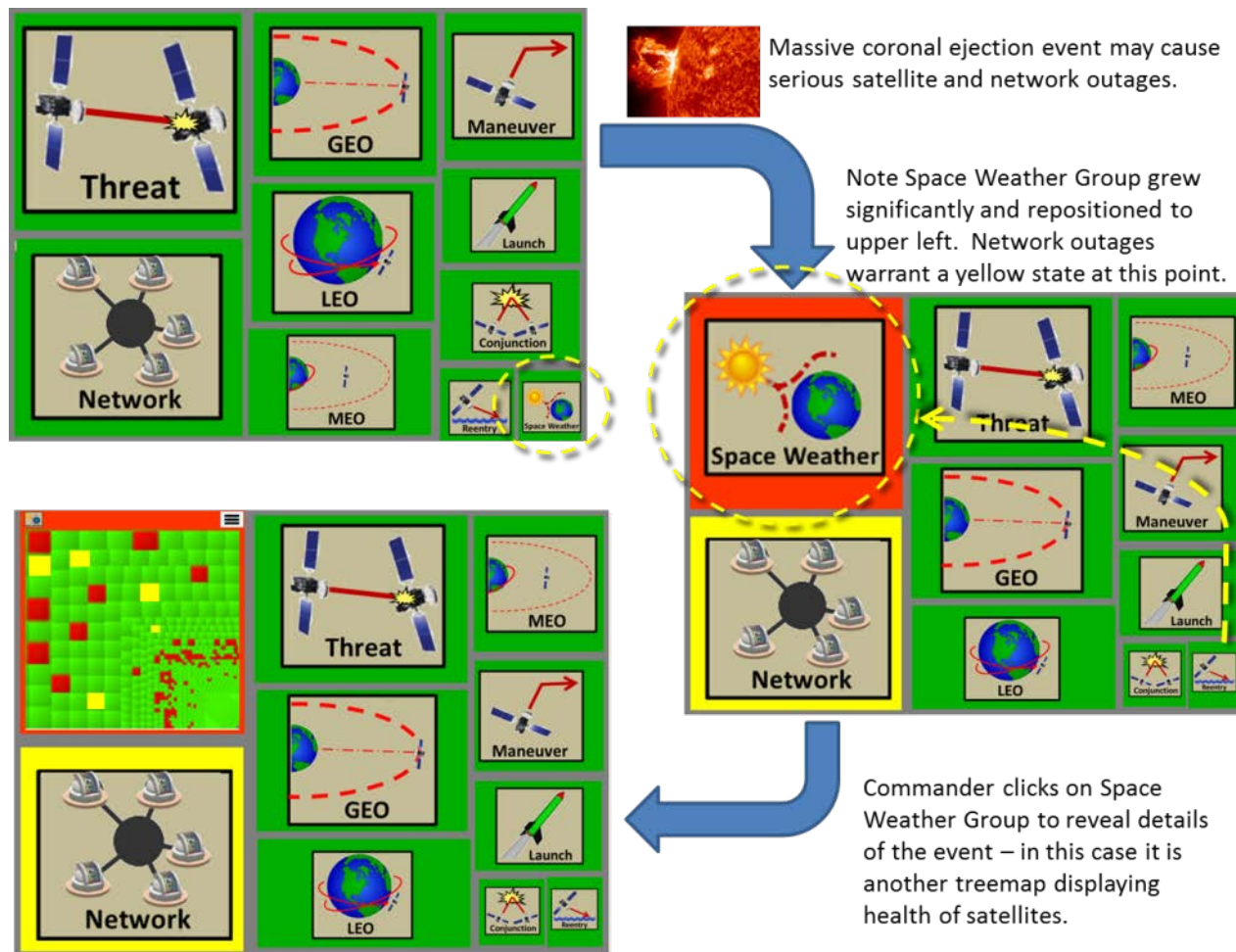
Fig. 11: Commander's Treemap example

The alert behavior would be controlled through a Group Editor like the one sketched in Fig. 12. This editor provides a simple method to establish a group name (annotation ❶ in Fig. 12), icon (❷) and initial size (❸). The initial size defines the importance of the group and thus the relative size of the rectangle compared to other groups. The Alert Section (❹-❿) is where alert conditions and treemap behavior is defined. In Fig. 12, there are five alert levels (❹ tabs) including two red (with growth factors of 2.0 and 3.0) plus blinking red that would likely signal a highly urgent situation. The first alert level – green in this case – is the default thus has no conditions to resize the group. The number of alert levels (tabs) can be changed by clicking the + tab (❺) to add a level or the cancel button (❻) to delete a level. The Growth Factor (❽) would be multiplied by the Initial Size upon entering that alert state (importance ✕ urgency). In this example, the size would double or triple in the red alert state depending on the urgency level. In the red blinking state, the tile would grow by 5.5 times. If the group has an underlying treemap, then ❿ can be used to define the alert conditions. This allows the user to perhaps select certain tiles that are of interest or exclude tiles. For example, the user could state "if any of the selected tiles are red, then this alert state should be activated."

Fig. 12: Group and Alert Editor

In cases where there is no digital data source available, a human expert would be able to insert an alert. This human-in-the-loop alert control may also be necessary in cases where a digital data source is indicating a known false alarm or exaggerating the urgency. Some organizations may want to designate a treemap foreman who makes the final decision as to how alerts are handled.

Although just a concept at this point, we feel that the Commander's Treemap would be useful on all types of displays – from smartphones to full wall displays. On smartphone sized touch displays, the more important groups would be larger and thus easier to touch for drill-down. On full wall displays in an operations center, the entire center could maintain awareness of operational state at a glance – even those in the back of the room.

5. SUMMARY

Treemapping shows promise to visualize large SSA data sets and convey urgency to commanders. These visualizations can provide a method to make use the screen space available to help make sense of large data sets on virtually any sized display – from smartphones to wall displays. With optimal use of the logical, one-touch drill-down capabilities, we have observed that users can become proficient in a small amount of time. If the rectangles are sized by importance and urgency, the most critical items will be the most visible and easy to touch. Wall displays in operational centers – often used for little more than cable news networks, video feeds and maps – can benefit from the ability to convey the current, big-picture status in a format that is easy to grasp from across the operational floor. Granted treemaps are not the solution for complete situation awareness, including geospatial and temporal, but may be an alternative for visualizing analytic trends and big picture data.

6. ACKNOWLEDGEMENTS

7. REFERENCES

[1]   Aleva, D and McCracken, J. (2009)"JSpOC Cognitive Task Analysis," 2009 Advanced Maui Optical and Space Surveillance (AMOS) Conference Proceedings.

[2]   Bruls, Mark; Huizing, Kees; van Wijk, Jarke J. (2000). "Squarified treemaps". In de Leeuw, W.; van Liere, R. Data Visualization 2000: Proc. Joint Eurographics and IEEE TCVG Symp. on Visualization (PDF). Springer-Verlag. pp. 33–42.

[3]   Covey, S., Merrill, A. R., and Merrill, R. R., *First Things First: To Live, to Love, to Learn, to Leave a Legacy*. New York: Simon and Schuster, 1994. (ISBN 0-684-80203-1)

[4]   Defense Advanced Research Projects Agency (2015) Tactical Technology Office OrbitOutlook, http://www.darpa.mil/Our_Work/TTO/Programs/OrbitOutlook.aspx, last accessed May 27, 2015.

[5]   Eisenhower, D.W. (1954) "Address at the Second Assembly of the World Council of Churches, Evanston, Illinois," August 19, 1954. Online by Gerhard Peters and John T. Woolley, The American Presidency Project.

[6]   Ghoniem, M. and Fekete, J., (2001) "Animating Treemaps", 18th Annual Symposium and Open House of Human-Computer Interaction Laboratory, Institute for Advanced Computer Studies, University of Maryland, http://www.cs.umd.edu/hcil/about/events/open-house-2001/animated_treemaps.pdf (last accessed June 26, 2015).

[7]   Macrofocus GmbH, (2015) US Presidential Elections, http://www.treemap.com/datasets/uselections/, last accessed May 27, 2015 (permission to reuse granted on 28 May 2015 in e-mail from Luc Girardin at Macrofocus).

[8]   Pavey, S. and the Mind Tools Team. (2015) "Eisenhower's Urgent/Important Principle: Using Time Effectively, Not Just Efficiently", http://www.mindtools.com/pages/article/newHTE_91.htm, last accessed June 16, 2015.

[9]   Shneiderman B. (1992), "Tree visualization with tree-maps: 2-d space-filling approach", ACM Transactions on Graphics, Jan., 1992, Vol 11, pp. 92-99..

[10]   United States Air Force, (2015) Space Track Space Surveillance System, at <www.space-track.org>. Last accessed June 26, 2015.

[11]   Wattenberg, Martin (2005). "A Note on Space-Filling Visualizations and Space-Filling Curves". In Stasko, John T.; Ward, Matthew O. IEEE Symposium on Information Visualization (InfoVis 2005), 23-25 October 2005, Minneapolis, MN, USA (PDF). IEEE Computer Society. p. 24.